Mars *In Situ* Resource Utilization (ISRU) and Planetary Protection

Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions

March 25, 2015

Gerald (Jerry) Sanders/NASA JSC
Rob Mueller/NASA KSC

What is In Situ Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

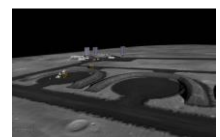
Five Major Areas of ISRU

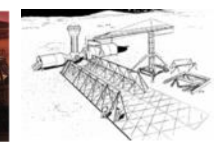
- **Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water



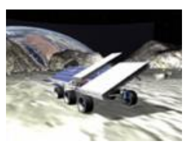

- **Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

- **Civil Engineering & Surface Construction**
  Radiation shields, landing pads, roads, habitats, etc.



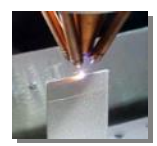







- **In-Situ Energy Generation, Storage & Transfer**
  Solar, electrical, thermal, chemical

- **In-Situ Manufacturing & Repair**
  Spare parts, wires, trusses, integrated structures, etc.



- **'ISRU' is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Planetary Protection Concerns for ISRU

- **Forward contamination: Biological traces introduced to Mars**

- **Creation of special region: liquid water at 'comfortable' temperatures for long periods of time**
  - COSPAR defines Special Regions as ''a region within which terrestrial organisms are likely to replicate''

- **Release of solids (dust grains) generated by excavation or drilling or reactor feeding spillover etc… after contact with machinery may be transported by winds and deposited somewhere else.**

- **Release of gases/liquids through leakage, venting operations, or failure that could confuse search for life**

Mars Resource & ISRU Process Options

Mars Resources

- Atmosphere
  - 6 to 10 torr pressure (~0.08 to 0.1 psi); +35 °C to -153 °C
  - 95.5% CO_2, 2.7% N_2, 1.6% Ar, 0.1% O_2, traces
- Soil
  - Minerals formed in liquid water environments
    - Phyllosilicates, sulfates, carbonates contain enhanced water content, to ~8 wt.%
    - Perchlorates 0.8 to 1 wt%
  - Water in different forms and concentrations (other charts)

Four Options for Mars ISRU Ascent Propellant Production:

1. Make O_2 and fuel/CH_4 from Mars atmosphere CO_2 and hydrogen (H_2) from Earth
   - Mars Sample Return mission studies: JPL and others
   - Mars Human Design Reference Mission 1.0 to 4.0
2. Make oxygen (O_2) from Mars atmosphere carbon dioxide (CO_2); Bring fuel from Earth
   - Mars Human Design Reference Mission 5.0 - baseline; methane fuel
   - JSC Mars Sample Return study 1995; propane fuel
3. Make O_2 and fuel/CH_4 from Mars atmosphere CO_2 and water (H_2O) from Mars soil
   - Mars Human Design Reference Mission 5.0 - option; methane fuel
4. Make O_2 and H_2 from H_2O in Mars soil
   - Considered but never selected due to volume and difficulties with liquefaction and storage of H_2

The Chemistry of Mars ISRU

2nd Step

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)

$2\,CO_2 \xrightarrow{900 - 1000\ C} 2\,CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)

$CO_2 + H_2 \xrightleftharpoons{400 - 650\ C} CO + H_2O$ [catalyst] → H_2O → WE to O_2

Bosch

$CO_2 + 2\,H_2 \xrightarrow{450 - 600\ C} C + 2\,H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → WE to O_2

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)

$CO_2 + 4\,H_2 \xrightleftharpoons{200 - 300\ C} CH_4 + 2\,H_2O$ [Ru catalyst] → H_2O, CH_4 → WE to O_2

Methane Reformer

$CO + 3\,H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → WE to O_2

Electrochemical Reduction

$CO_2 + 2\,H_2O \rightarrow CH_4 + 2\,O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)

$n\,CO + (2n+1)\,H_2 \xrightarrow{>150\ C} C_nH_{2n+2} + n\,H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → WE to O_2

Methanol

$CO + 2\,H_2 \xrightarrow[50 - 100\ atm]{250\ C} CH_3OH$ [ZnO catalyst] → CH_3OH

$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → WE to O_2

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)

$2\,H_2O \rightarrow 2\,H_2 + O_2$ → O_2, $2\,H_2$

Steam Reforming

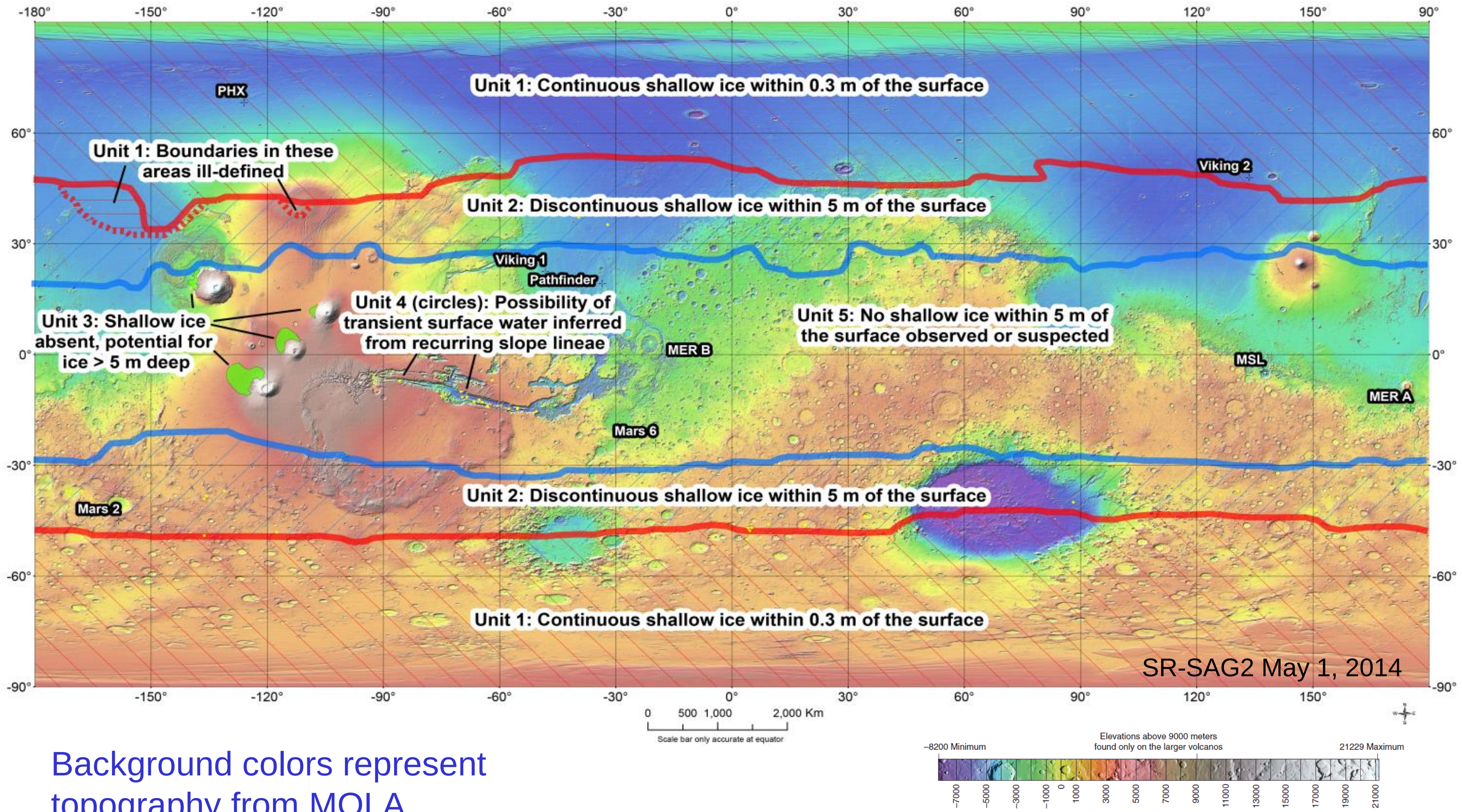
$H_2O + CH_4 \rightarrow 3\,H_2 + CO$ → $3\,H_2$

Dry Reforming

$CO_2 + CH_4 \rightarrow 2\,H_2 + 2\,CO$ → $2\,H_2$

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Preliminary Map of Water Distribution and Regions on Mars

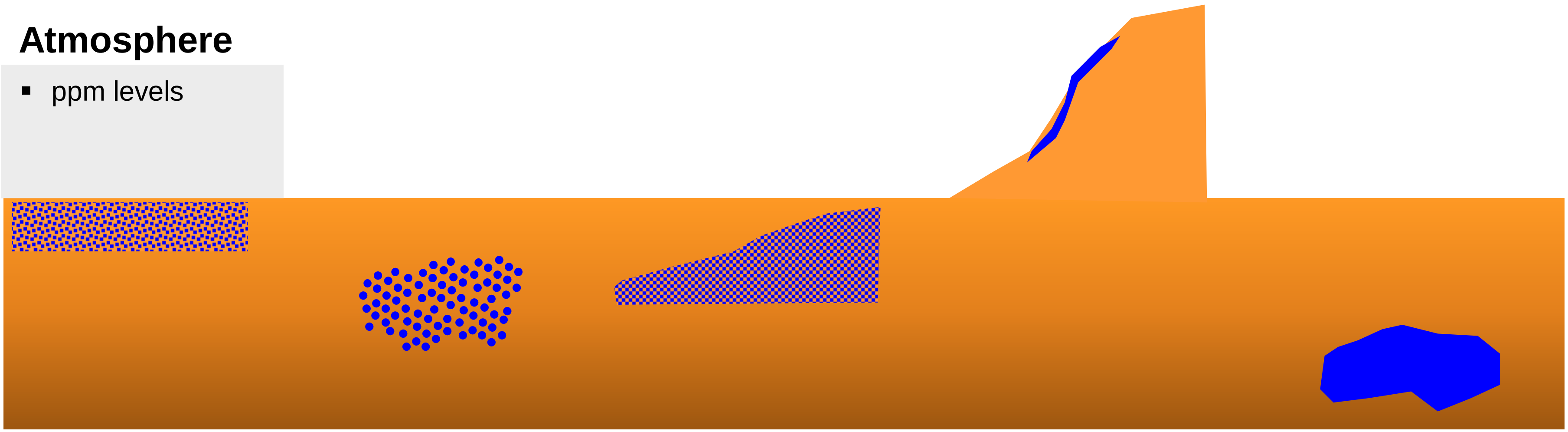


Background colors represent topography from MOLA.

Water on Mars
(Simplified)

Atmosphere

- ppm levels



Hydrated Soil

- Water of hydration in minerals
- <2 to ~13% by mass
- Primary at equator and lower latitudes
- At/near surface

Permafrost

- Subsurface ice/permafrost within the top 5 meters in the mid latitudes
- Deeper ice/ permafrost may exist at lower latitudes
- Concentration %?

Icy Soils

- Shallow, nearly pure ice in newly formed craters in mid-upper latitudes. Fresh impacts expose ice excavated from 0.3-2.0 meters depth
- Dirty ice at polar locations: Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms

Recurring Slope Lineae (RSL)

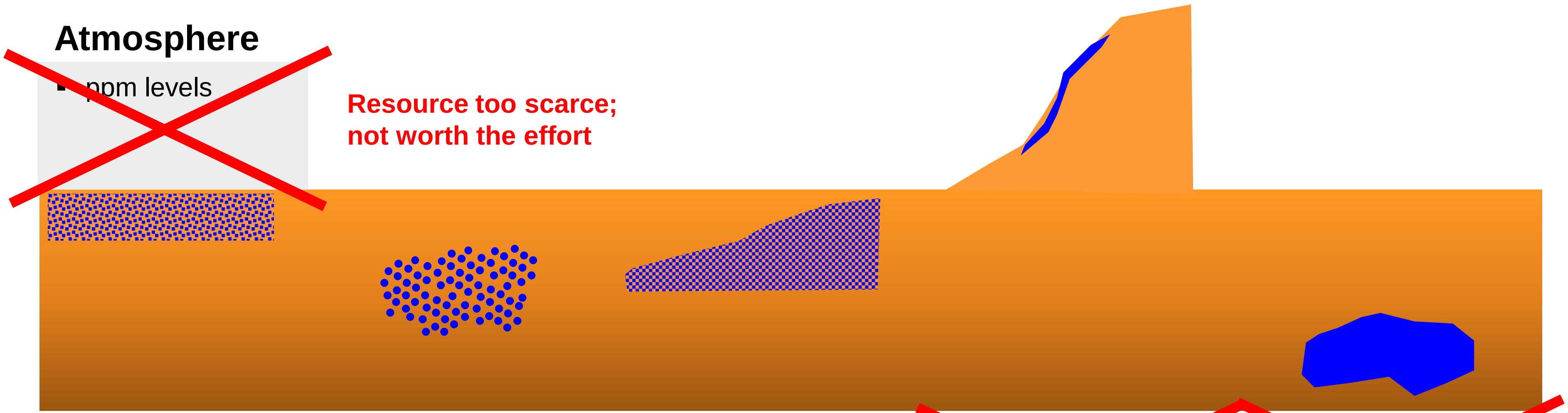
- Briny water has been theorized as cause of RSLs.
- Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range

Aquifers

- Suspected to be >1 km below surface

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Water on Mars
(Simplified)



Hydrated Soil

- Water of hydration in minerals
- <2 to ~13% by mass
- Primary at equator and lower latitudes
- At/near surface

Permafrost

- Subsurface ice/permafrost within the top 5 meters in the mid latitudes
- Deeper ice/ permafrost may exist at lower latitudes
- Concentration %?

Icy Soils

- Shallow, nearly pure ice in newly formed craters in mid-upper latitudes. Fresh impacts expose ice excavated from 0.3-2.0 meters depth
- Dirty ice at polar locations: Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms

~~Recurring Slope Lineae (RSL)~~

- Briny water has been theorized as cause of RSLs.
- Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range
- **RSL sites and possibly the active gullies are Special Regions**.

~~Aquifers~~

- Suspected to be >1 km below surface
- **Possible Special Region**

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Determining 'Operationally Useful' Resource Deposits

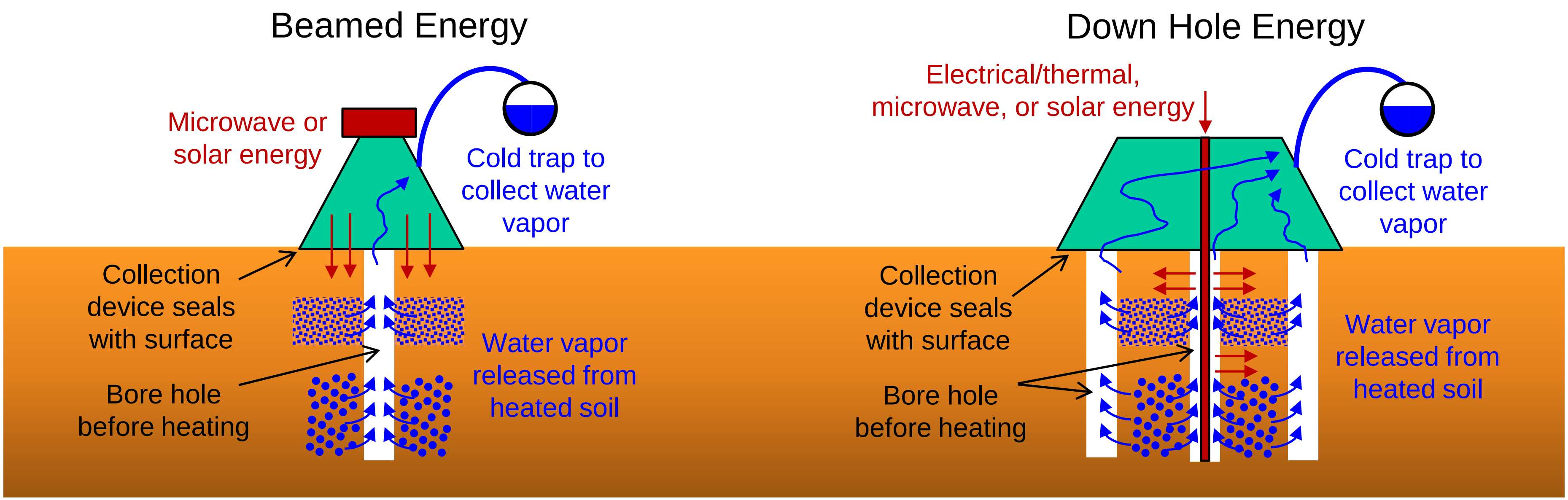
Whether a resource is 'Operationally Useful' is a function of its *Location* and how *Economical* it is to extract and use

- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
  - Resource must be within reasonable distance of transportation and delivery of product to 'market': habitats, landers, orbital depots, etc.

- **Resource extraction must be 'Economical'**
  - Concentration and distribution of resource and processing technique allows for Return on Investment (ROI) for:
    - Mass ROI - mass of equipment and unique infrastructure compared to brining product and support equipment from Earth
    - Cost ROI - cost of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - Time ROI - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
    - Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth: launch mass limits for radiation shielding, time gap between need and delivery, etc.
  - Amount of product needed justifies investment in extraction and processing
    - Requires long-term view of exploration and commercialization strategy to maximize benefits

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

In Situ Water Extraction from Mars Soils



- Energy heats soil so that water converts to vapor (may transition thru liquid phase)
- Release of water helps further heat conduction into soil
- Water vapor follows 'path of least resistance' to bore hole
  - Vapor may also re-condense away from heat in colder soil
- Water vapor collected in cold trap in liquid/solid form
- Process may take hours

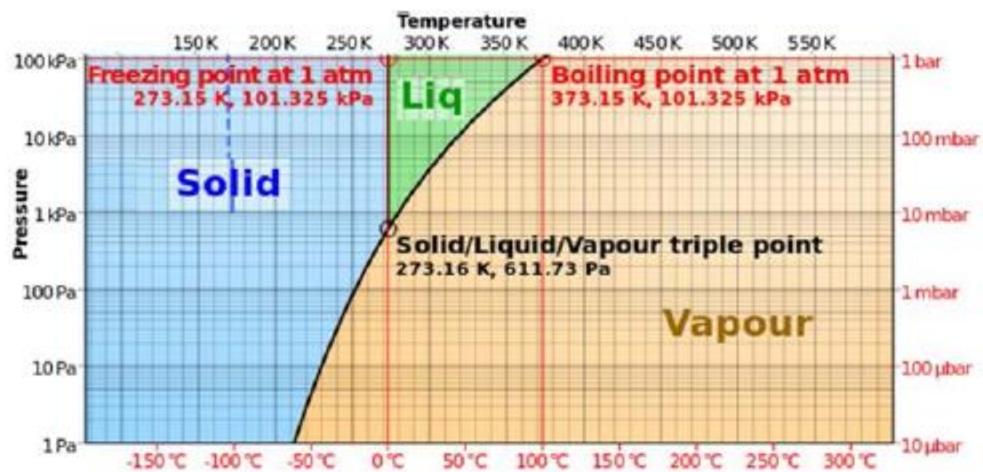
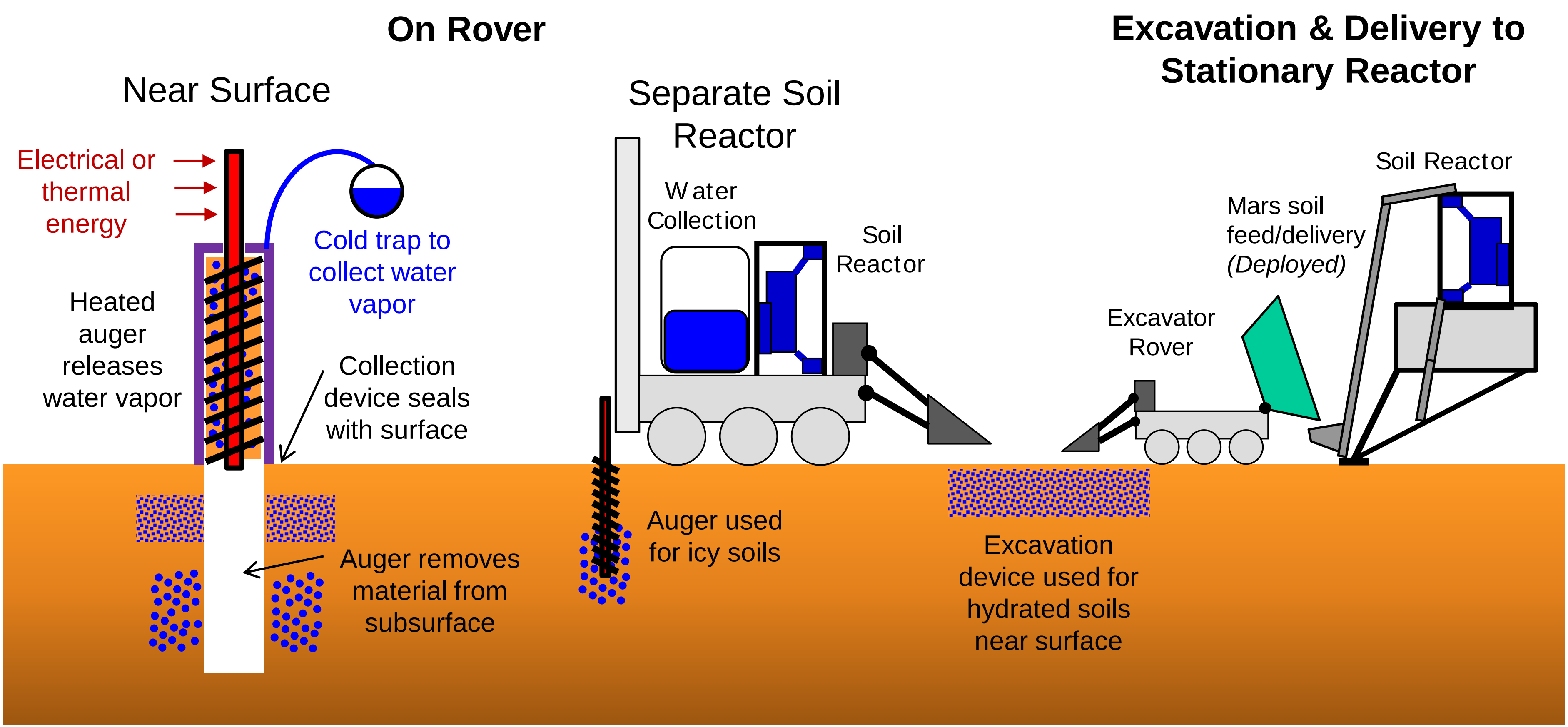


Figure 1. Phase diagram of water near the triple point.

Water Extraction via Excavation & Processing Reactor



- Soil is removed from subsurface
- Soil is heated via thermal to remove water vapor; can be higher temperature than *in situ* heating
- Soil is removed from surface/subsurface and transferred to soil reactor
- Soil is heated via thermal, microwave, and/or gas convection to remove water vapor at higher temperatures and pressures than for *in situ* heating
- Water vapor is condensed and stored
- Soil is dumped back onto surface after processing

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Water/Volatiles Released from Mars Soil
(SAM instrument: Rocknest sample)

Region 1: <300°C
- 40-50% of the water released
- Minimal release of HCl or H_2S

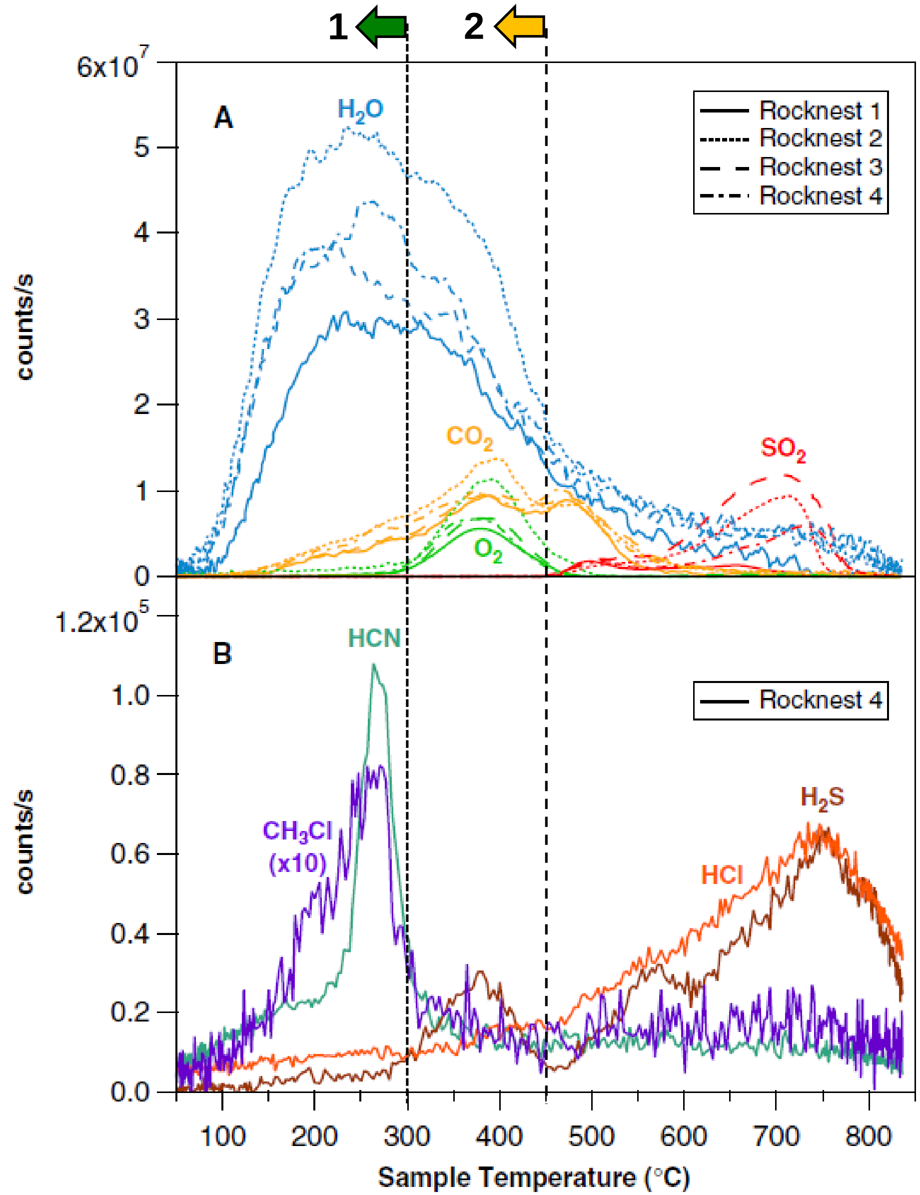
Region 2: <450°C
- >80% of the water released
- CO_2 and O_2 released from decomposition of perchlorates
- Some release of HCl or H_2S but before significant amounts are release

Predicted Volatile Release Based on Lab Experiments

CO_2 released by
1. Absorbed atmosphere <200°C
2. Oxidation of organic material >200°C
3. Thermal decomposition of carbonates >450°C

O_2 released by
1. Dehydroxylation of clays <350°C
2. Decomposition of non-metal and metal oxides >500°C

CH_3Cl and CH_2Cl_2 released by
1. Decomposition of $Mg(ClO_4)_2$ perchlorate >200°C



L.A. Leshin.,et. al.., "Volatile, Isotope, and Organic Analysis of Martian Fines with the Mars Curiosity Rover", Science 341 (2013), DOI 10.1126/science.1239937

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

ISRU Water Prospecting and Science

- **Both science and ISRU want to better understand the form and distribution of water on Mars and the geological context in which it is found**
- **ISRU wants understanding over 100's of meters to kilometers around potential human landing sites**
- **Some combination of capabilities and instruments from missions below is highly desirable**

Mission	Terrain	Physical	Mineral	Volatile	Environment
Mars Exploration Rovers	Panoramic Camera	Microscopic Imager Rock abrasion tool	Panoramic Camera Alpha Proton X-ray Spec Mossbauer Spectrometer Miniature Thermal Emission Spectrometer		
Mars Curiosity Rover	Mast Camera	Mars Hand Lens Imager Sample Drill (cm)	Alpha Proton X-ray Spec Laser Induced Breakdown Spectroscophy (LIBS) X-Ray Diffraction/X-Ray Fluorescence	SAM Gas Chromatograph/ Mass Spectometer; TDL Neutron Spectrometer w Pulsing Neutron Gen.	Environment Monitoring Station Radiation Detector
ExoMars	Mast Camera	Ground Penetrating Radar Sample Drill (2 or 3 m)	Micro infrared imaging spectrometer Raman Spectrometer X-Ray Diffraction Mossbauer Spectrometer Infrared Spectrometer	GC-MS and Laser Desorption Ion Source	
Resource Prospector RESOLVE	Mast Camera	Sample Drill (1 m)	Near Infrared Spectrometer	GC-MS Near IR Neutron Spectrometer	
RLEP 2 (Proposed)	Mast Camera	Sample Drill (2) Arm/scoop Cone penetrometer/shear vane		Neutron spectrometer Ground Penetrating Radar GC-MS with TDL	

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Primary ISRU Products and Venting/Leakage

- **Oxygen**
  - 100% pure from CO_2 electrolysis (CO or CO_2 if cell leaks but can monitor)
  - Pure from water electrolysis; traces of water and/or contaminant from regenerative dryer may be present before liquefaction

- **Fuel Production Options**
  - Methane: Produced from Sabatier reaction: traces of CO_2 and H_2 may be present and vented
  - Fischer-Tropsch Hydrocarbons: ethane, butane, ethylene, kerosene
  - Aromatics; benzene, toluene

- **Water**
  - From soil: turned to steam but could include HCN, CH_3Cl, CH_2Cl_2, H_2S, HCl
  - From trash: may include CO, CO_2, SO_2, NO_2, and traces of organics

- **Nitrogen**
  - From atmosphere after CO_2 removal; freeze separation could include traces of atmosphere gases

Mars Water ISRU and Planetary Protection

Proposed rules/guidelines: ISRU excavation and soil processing can be performed on Mars as long as

- The excavation devices and soil processing hardware are sterilized before launch;
  - This includes any water or other reactants that might be launched from Earth to support startup operations
- No *in situ* heating of soil where water will be or reside in liquid form for 'long periods' of time.
  - Duration of operation will need to be defined and approved before launch
- No *in situ* liquid water resources are used (subterranean aquifers or RSLs)

Since soil reactors will most likely operate at >300 °C for >1 hour, there should be minimal concern about dumping processed soil.

Leakage of ISRU reactants and products may confuse search for life effort but will not cause planetary protection issues

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

What Can ISRU Do for Planetary Protection?

- **Trash Processing to sterile ash and propellant**
- **Production of sterilizing fluids**

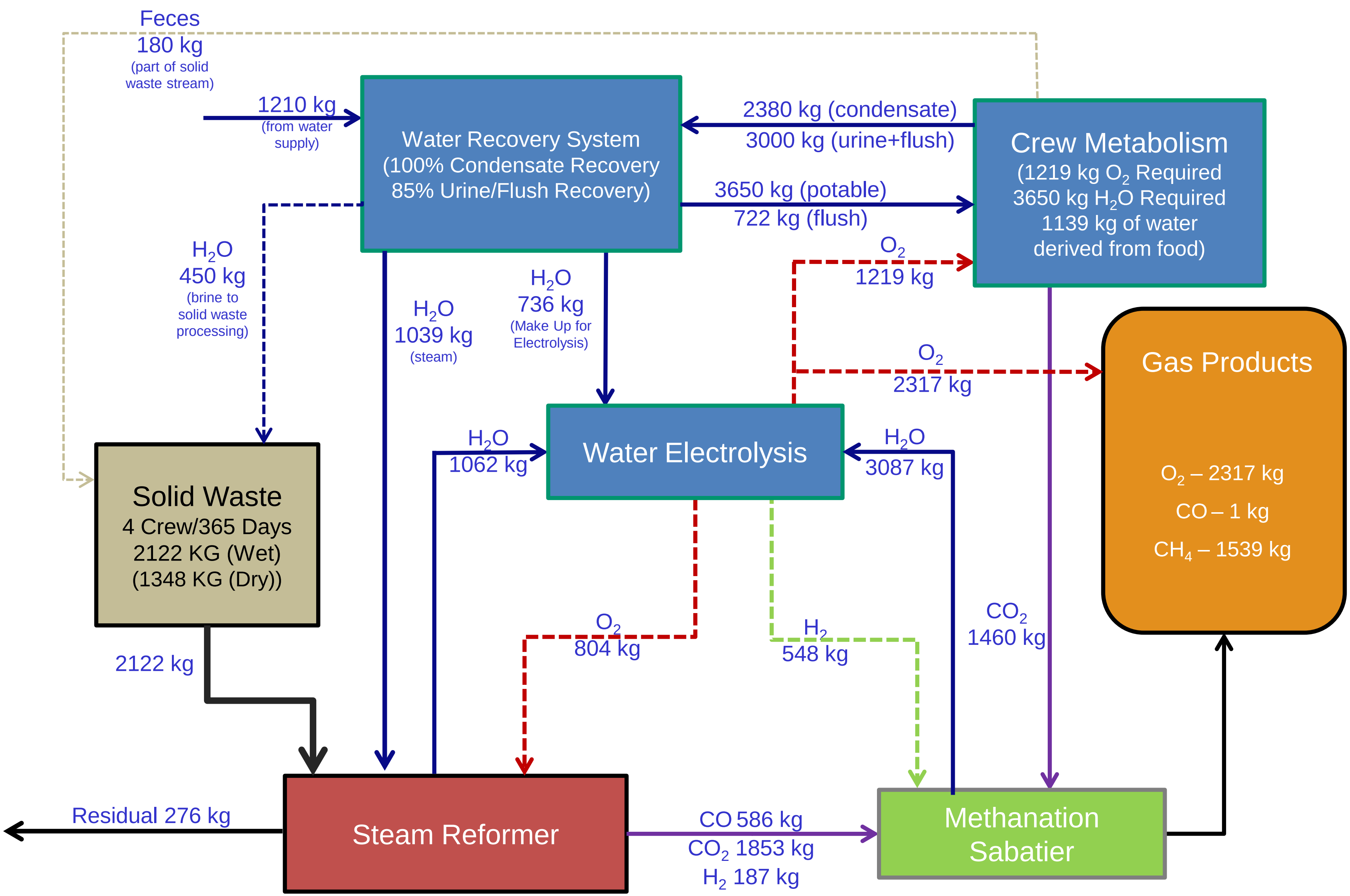
What Can ISRU Do for Planetary Protection?

- **Trash Processing to sterile ash and propellant**

- **Production of sterilizing fluids:**
  - Hydrogen peroxide
  - Ammonia
  - Alcohol; *but for medicinal purposes only of course*

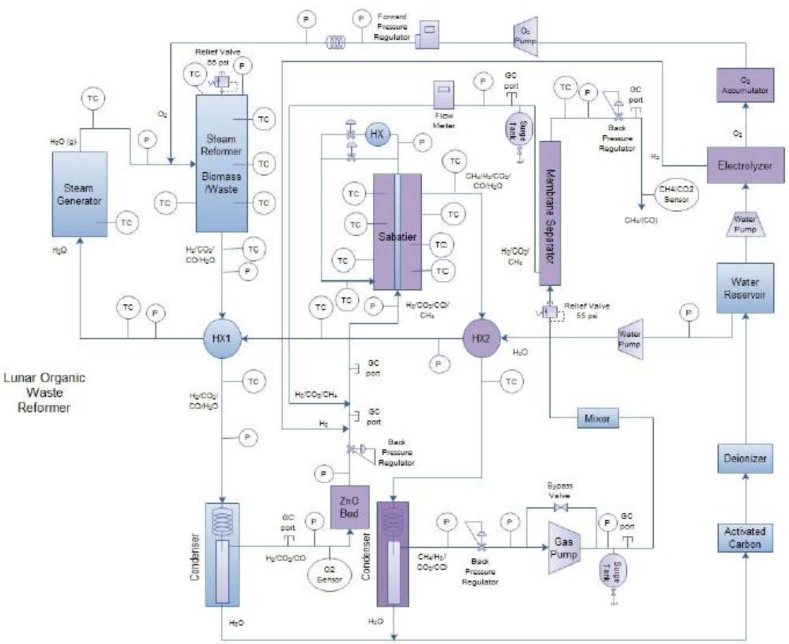
Solid Waste to Gas Conversion using Steam Reformer

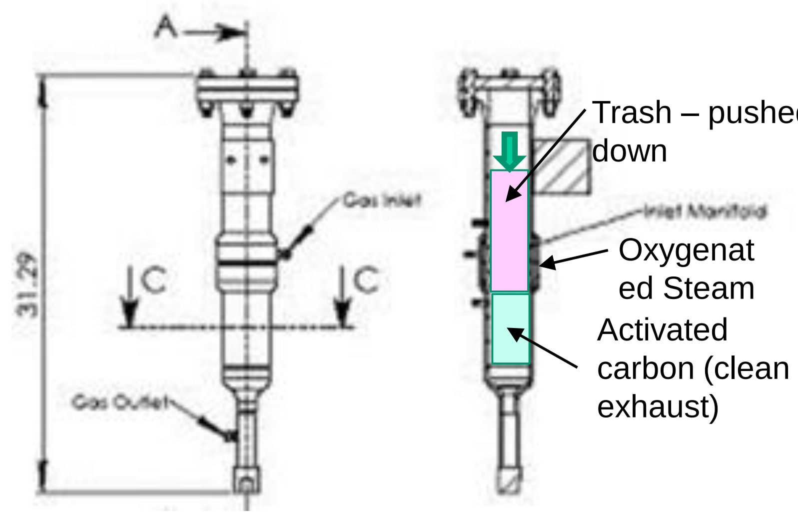
(from 6 Aug 2013 down select TIM)



Trash/Carbon Waste Oxidation/Steam Reforming
(Pioneer Astronautics)

- At reformer temperatures above 700°C, oxygenated steam reacts with organic matter to produce a gas mixture largely composed of hydrogen, carbon monoxide, and carbon dioxide.
- Water from trash processing is condensed
- Dry reformer exhaust gases are fed to a catalytic Sabatier reactor where they are combined with supplemental hydrogen at 350-500°C to produce methane and water.
- System is sized to process 5.4 kg of waster per day (4 person crew)
  - **3.251 kg O_2/day; 2.236 kg CH_4/day; 0.595 kg H_2O feed)**





G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Background

Mars ISRU Mission Studies

- **Past Mars Studies with ISRU (DRM 1 to 4)**
  - Only considered atmospheric resources were available (CO_2, N_2, Ar)
  - Evaluated two propellant production options
    - Make Oxygen (O_2) only and bring fuel from Earth
    - Make O_2 and methane (CH_4) with hydrogen (H_2) brought from Earth
  - Produced various amounts of life support consumables as backup
    - Ex. DRM 3: 4500 kg of O_2; 3900 kg of N_2 ; 23,200 kg of water (H_2O)
  - ISRU considered only after performing non-ISRU scenario
    - No change in Mars entry or rendezvous orbit compared to non-ISRU scenario
    - Influence of ISRU consumable availability or technologies not considered on other systems
  - Decisions made on basis of mass/power comparisons. Did not evaluate volume required for ISRU hardware or hydrogen delivered from Earth

- **Recent Mars Studies with ISRU**
  - Considered both atmospheric (CO_2, N_2, Ar) and soil (H_2O) resources based on increasing knowledge from Mars Odyssey and subsequent missions

1. Mars Design Reference Architecture (DRA) 5.0 – 2007
   - First study to consider water as a resource; understanding of water on Mars and ISRU hardware for soil excavation and processing was very preliminary
2. Mars Collaborative Study (HEOMD, STMD, SMD) – 2013
   - Increased understanding of water on Mars and ISRU hardware needed for soil processing based on lunar ISRU development and ISRU analog field test experience
3. Mars ISRU Payload for Supersonic Retro Propulsion (SRP) Mission – 2014
   - First study to examine volume/packaging of ISRU production options

Mars Resource & ISRU Process Options

	ISRU Resource Processing Options	ISRU Products	Mars Resource(s)	Earth Supplied		Process Subsystems/Options									
						CO_2 Collection & Conditioning	Solid Oxide CO_2 Electrolysis	Reverse Water Gas Shift (RWGS)	Sabatier	Bosch	Liquid Water Electrolysis	Solid Oxide H_2O Electrolysis	Ionic Liquid Electrolysis	Soil Processing	Soil Excavation & Delivery
Enabling	Atmosphere Processing	O_2	CO_2	CH_4 (~6600 kg)	1	X	X								
					2	X		X			X				
						X				X	X				
						X							X		
		O_2, CH_4, H_2O		H_2* (~2000 kg)		X	X		X			X			
						X		X	X		X				
						X							X		
Enabling or Enhancing	Soil Processing	O_2, CH_4, H_2O	H_2O	CH_4 **(~6600 kg)							X			X	X
	Atmosphere & Soil Processing	O_2, CH_4, H_2O	CO_2 & H_2O		3	X			X		X			X	X
						X			X			X		X	X

*H_2 for water and methane production

**Assumes methane fuel vs hydrogen fuel for propulsion

1, 2, & 3 Were Evaluated in Mars DRA 5.0

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

Water on Mars Summary

- **Water can be found on Mars from very low concentrations (<2% by mass) at the equator to very high concentrations (dirty ice) at the poles**

- **Water may be found in several forms based on the location on Mars**
  1. Water of hydration in minerals (<2 to ~13% by mass) – primary at equator and lower latitudes
  2. Subsurface ice/permafrost within the top 5 meters in the mid latitudes
  3. Shallow, nearly pure ice in newly formed craters in mid-upper latitudes
  4. Dirty ice at polar locations
  5. Recurring slope lineae (RSL) may be water??? Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range
  6. Subterranean aquifers???
  - Note:
    a. Forms 1 & 2 are the most likely resource based on potential landing locations
    b. Forms 5 & 6 are most likely not of interest for ISRU due to access difficulty (5) and planetary protection (6)

- **Most of the water in the soil can be removed by heating to <450°C**
  – >80% of the water released
  – CO_2 and O_2 released from decomposition of perchlorates (est. to be <0.8% by mass)
  – Some release of HCl or H_2S but before significant amounts are release at higher temperatures

Water Resources: SR-SAG 2 (1)

- **Equatorial Region (between 30°S and 30°N)**
  - Areas of H_2O enhancement (from Mars Odyssey neutron analysis) within equatorial region are usually interpreted as being due to hydrated minerals, which may contain water contents up to ~13%.
  - Ice deposits from past periods of high axial tilt remain at depth (>15 m) in localized regions, such as northwest of the Tharsis volcanoes.
  - Impact crater analysis, radar data, and neutron spectrometer data suggest that subsurface ice is generally located at depths >5 m in this region and often >50 m depth.
  - Recurrent Slope Lineae (RSL) sites and potential active gullies suggest presence of near-surface liquid in certain locations.
  - RSL sites and possibly the active gullies are Special Regions. Other locations are not Special.
  - Accessibility limitations: High levels of solar energy and warmest temperatures on the planet, but limited accessibility to H_2O.

- **Mid-Latitudes (30°-60° latitude)**
  - Geomorphic evidence of ice-related features emplaced during period of high axial tilt.
  - Geomorphic evidence of features produced by possible fluvial activity in past (gullies, layered deposits in craters, etc.)
  - Fresh impacts expose ice excavated from 0.3-2.0 meters depth.
  - Region where ice deposition can occur during periods of high axial tilt
  - RSL activity concentrated in this zone, particularly in southern hemisphere.
  - RSL sites are treated as Special Regions. Other regions in this zone not considered to be Special unless heated to melting or some future observation points to the natural presence of water.
  - Accessibility limitations: Energy produced by solar power limited to summer season

Water Resources: SR-SAG 2 (2)

- **High Latitudes (60° - 80° latitude)**
  - Region largely covered by seasonal caps during winter season
  - As seasonal caps retreat in spring, frost outliers (both CO_2 and H_2O) are left behind
  - Region surrounding north polar cap largely comprises the Vastitas Borealis Formation, interpreted as composed of ice-rich fine-grained (dust) deposits and ice-rich sediments from ancient fluvial activity.
  - Ice-rich fine-grained deposits also seen surrounding south polar cap, but much thinner than in north.
  - Geomorphic features in this region suggest ice-rich flow associated with glacial activity both today and in past
  - New fresh impacts in this region expose ice excavated from depths ranging from 0.3 m to 1.7 m.
  - Not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Same as polar caps

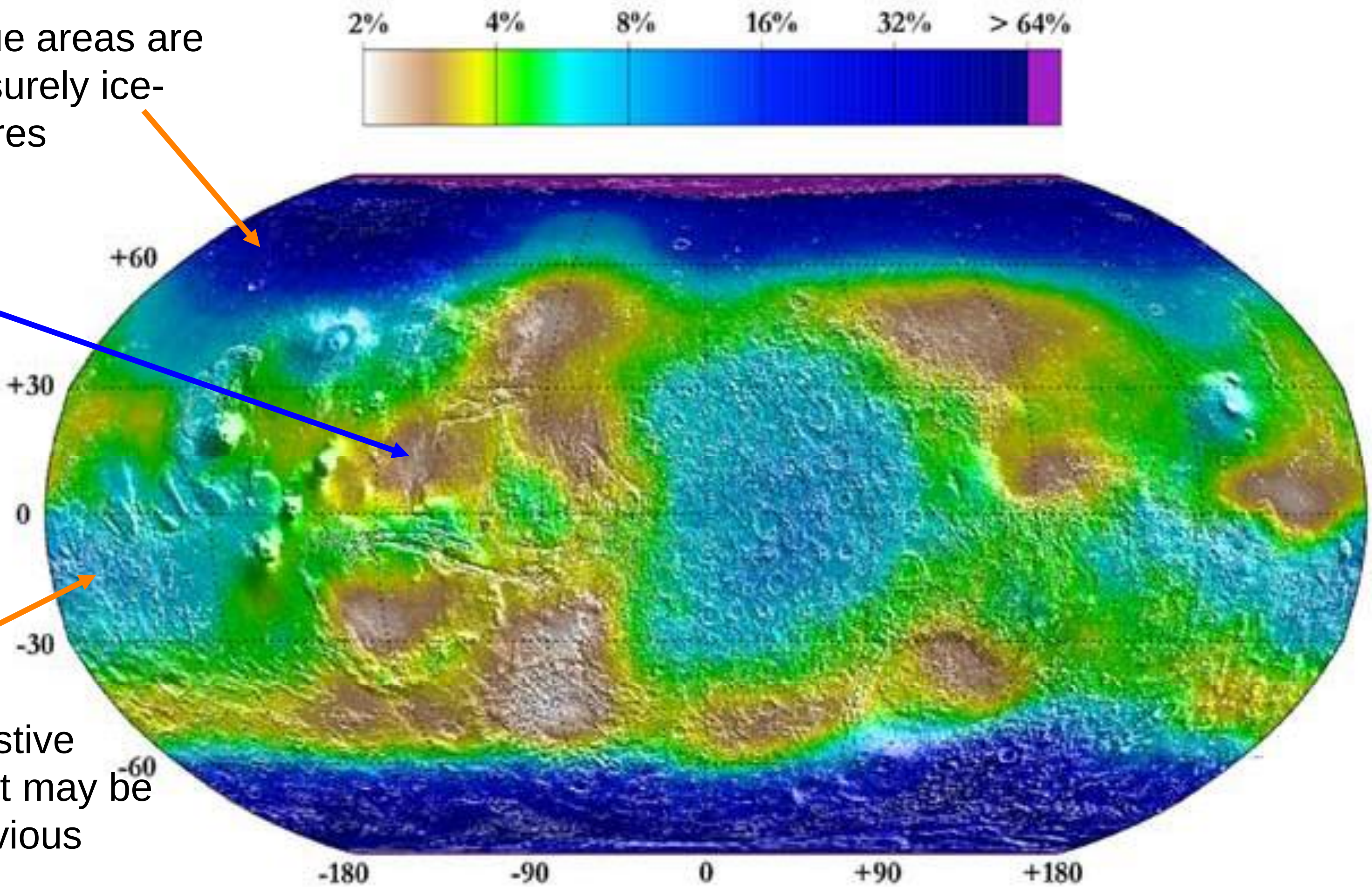
- **Polar caps (poleward of ~80° latitude)**
  - Seasonal caps are CO_2 ice.
  - Permanent south polar cap is H_2O covered by ~8 m thick veneer of CO_2 ice.
  - Permanent north polar cap is H_2O ice
    - ~3 km thick, 1100-km diameter
    - Volume estimated between 1.1 and 2.3 x 10^6 km^3. Freshwater content estimated to be ~100x the amount in North American Great Lakes.
    - Ice accessible at surface
    - Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms
  - Polar caps are not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Polar night darkness and cold limit useful season; CO_2 degassing in area may affect safe access by human explorers

Water Distribution in top ~ 1 meter on Mars

Dark blue areas are almost surely ice-filled pores

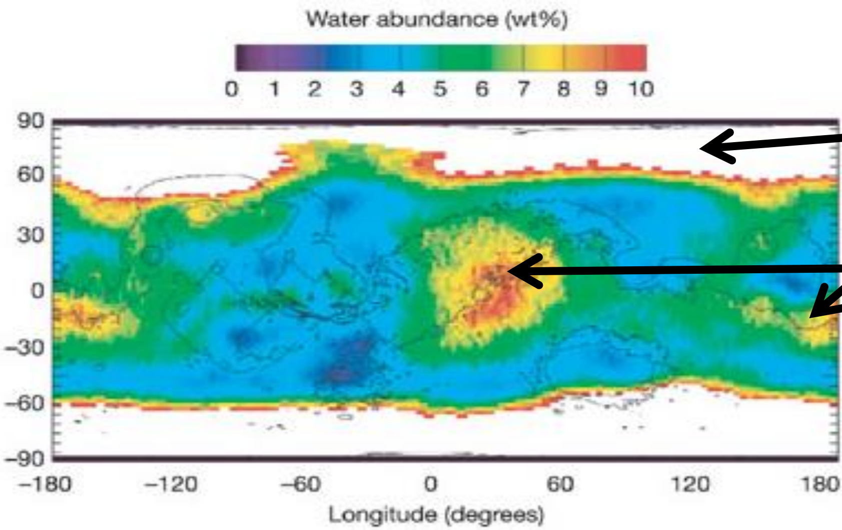
Low H_2O areas are likely to be bound water in minerals

Light blue areas are regions of high albedo and low thermal inertia suggestive of subsurface ice, that may be left over from the previous Mars ice age



G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov

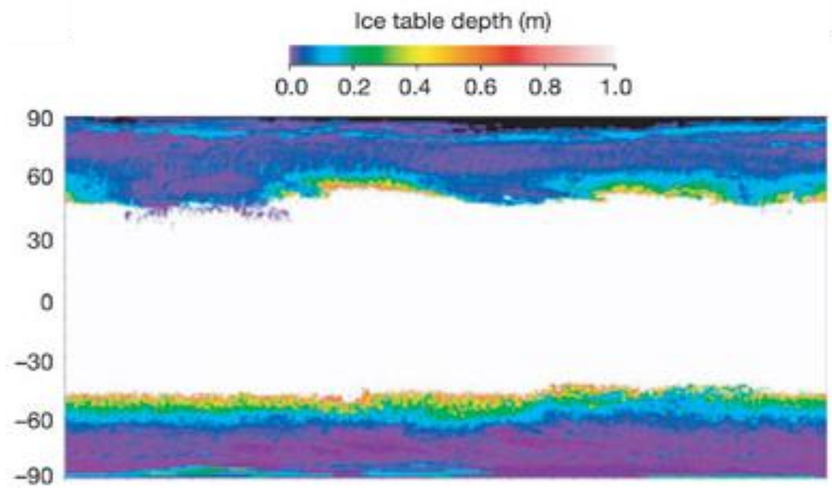
Water Form & Distribution Update

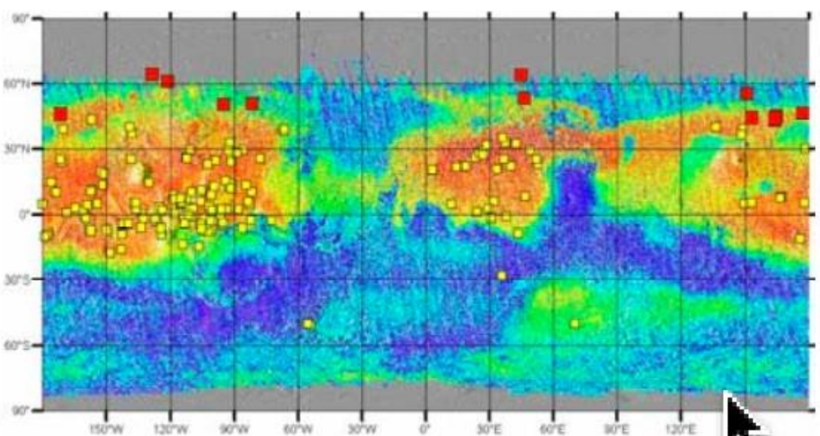


Mid- and high-latitude shallow ice

Thought to be dominated by hydrated minerals

Mid-Latitude Ice-Rich Mantles



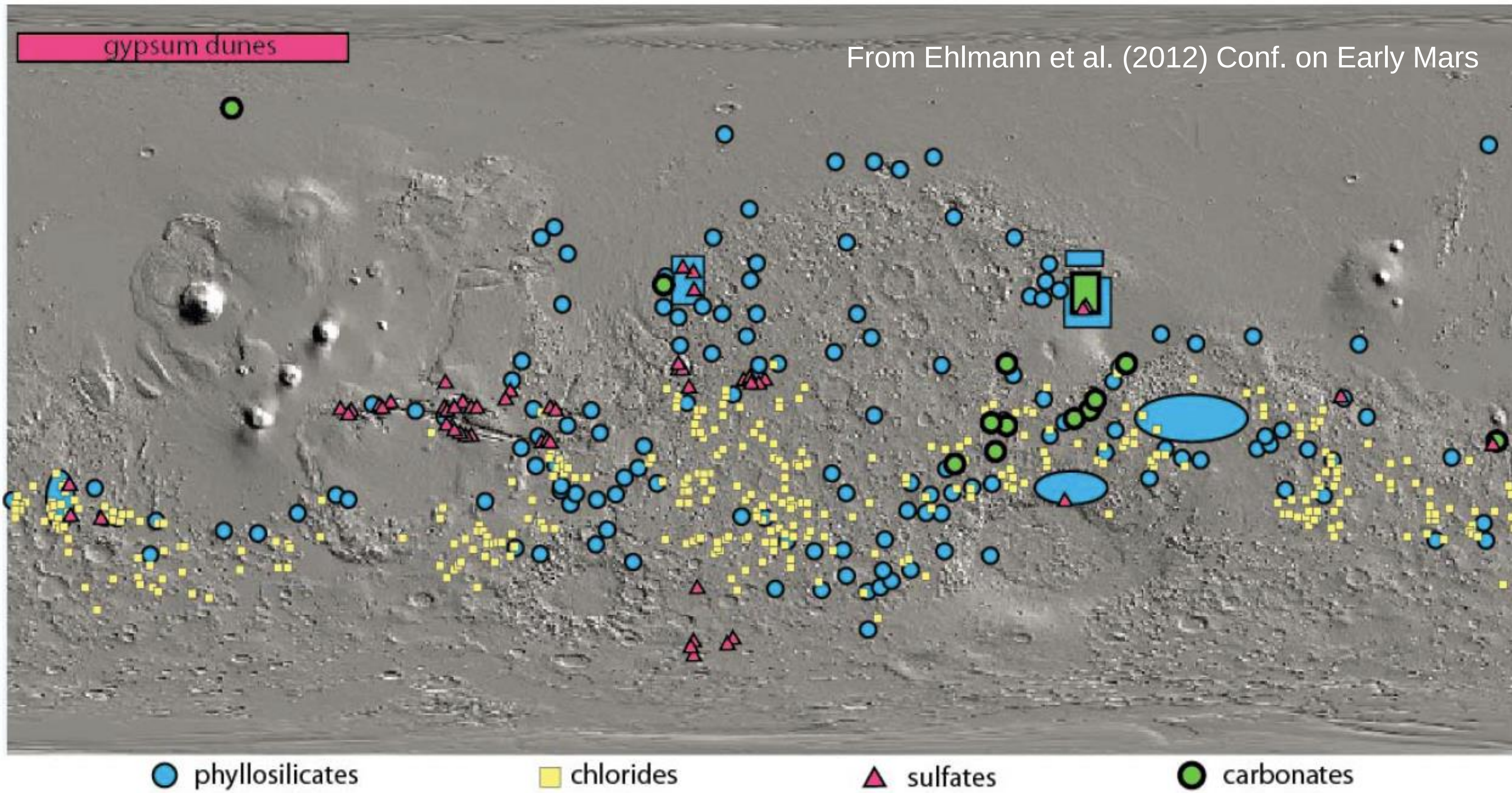


New Craters Confirm Shallow, Nearly Pure Ice

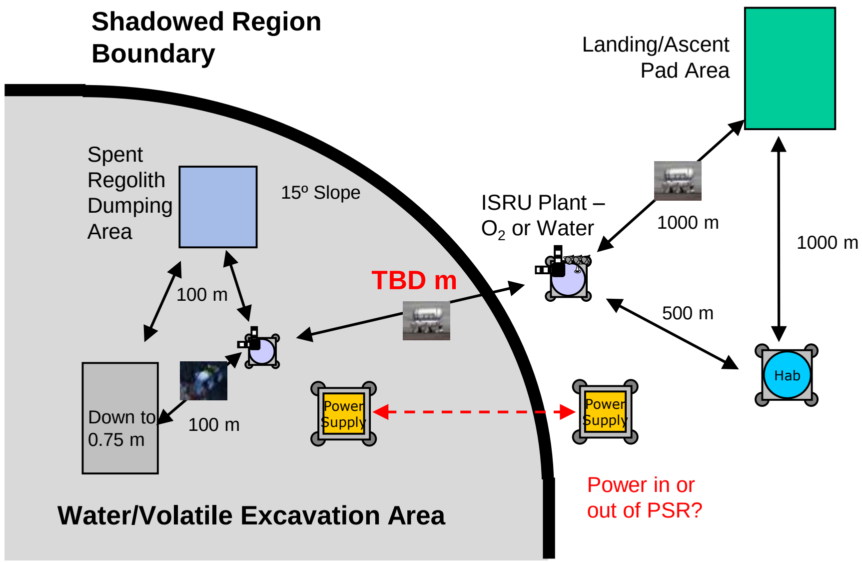
- Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)

"Aqueous Mineral" Distribution

- Minerals formed in liquid water environments
- Phyllosilicates, sulfates, carbonates contain enhanced water content, to ~8%
- Exposed in areas without mid-latitude mantle



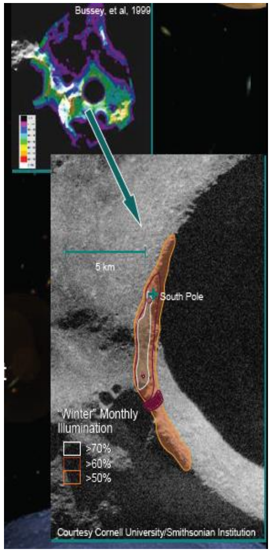
Determining 'Operationally Useful' Resource Deposits - *Location*



Polar region
- Solar >70% per year with 100 hr max. eclipse periods
- Highland regolith (iron poor)

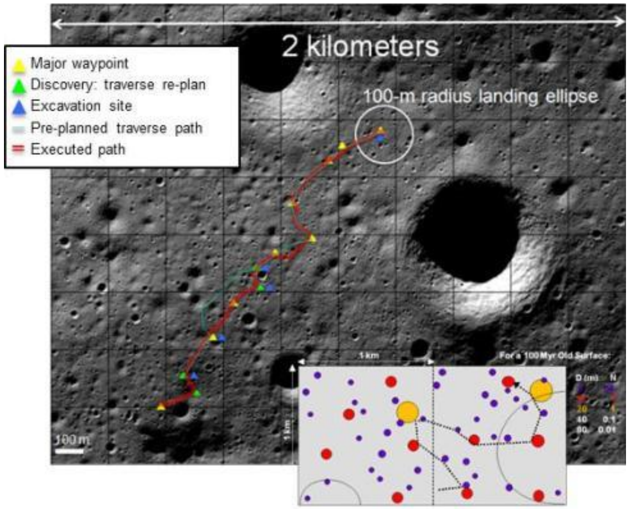
Permanently Shadowed Crater
- Nuclear power, power cable, or power beamed for elements that stay in the crater.

Equatorial region
- Solar 50% per year with 28+ day/night cycle
- High titanium/iron oxide mare

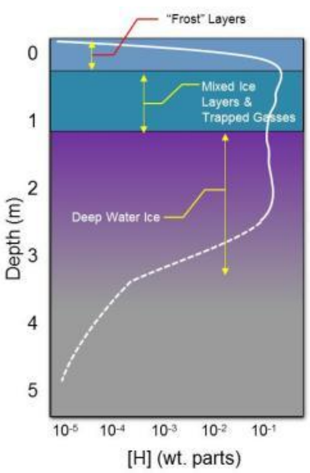


Need to assess the extent of the resource 'ore body'

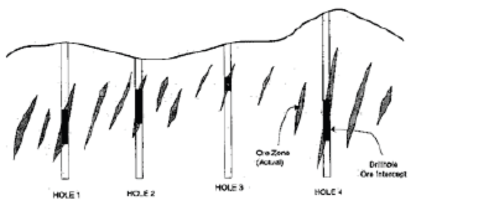
Need to Evaluate Local Region (1 to 3 km)



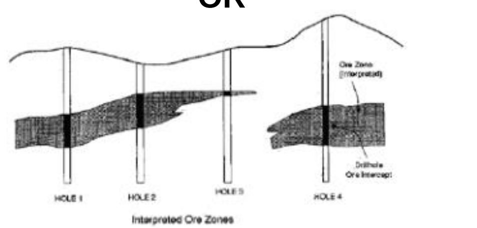
Need to Determine Vertical Profile



Need to Determine Distribution



OR



Determining 'Operationally Useful' Resource Deposits - *Economics*

An 'Operationally Useful' Resource Depends on What is needed, How much is needed, How often it is needed, and What is required to extract the resource

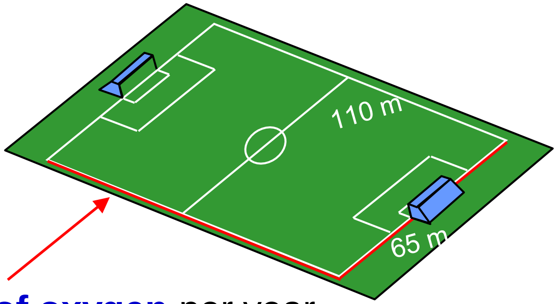
Potential Lunar Resource Needs

- 1,000 kg oxygen (O_2) per year for life support backup (crew of 4)
- 3,000 kg of O_2 per lunar ascent module launch from surface to L_1/L_2*
- 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L_1/L_2 (fuel from Earth)*
- 30,000 kg of O_2/Hydrogen (H_2) per reusable lunar lander to L_1/L_2 (no Earth fuel needed)*

***Note: ISRU production numbers are only 1st order estimates for 4000 kg payload to/from lunar surface**

Mining Equipment – Oxygen Extraction

- Excavation rates required for 10 MT O_2/yr production range based on Oxygen extraction efficiency of process selected and location
  - Hydrogen reduction at poles (~1% extraction efficiency): 150 kg/hr
  - Carbothermal reduction (~14% extraction efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr

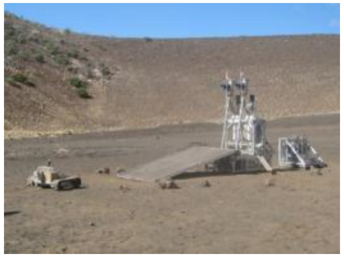


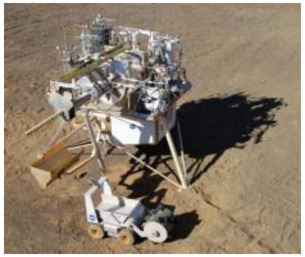
10 MT of oxygen per year requires excavation of a soccer field to a depth of 0.6 to 8 cm! **(1% & 14% efficiencies)**

- Laboratory tests showed high excavation rates of 150 to 250 kg/hr for **SMALL** excavation vehicle (<150 kg)

Cratos Excavator

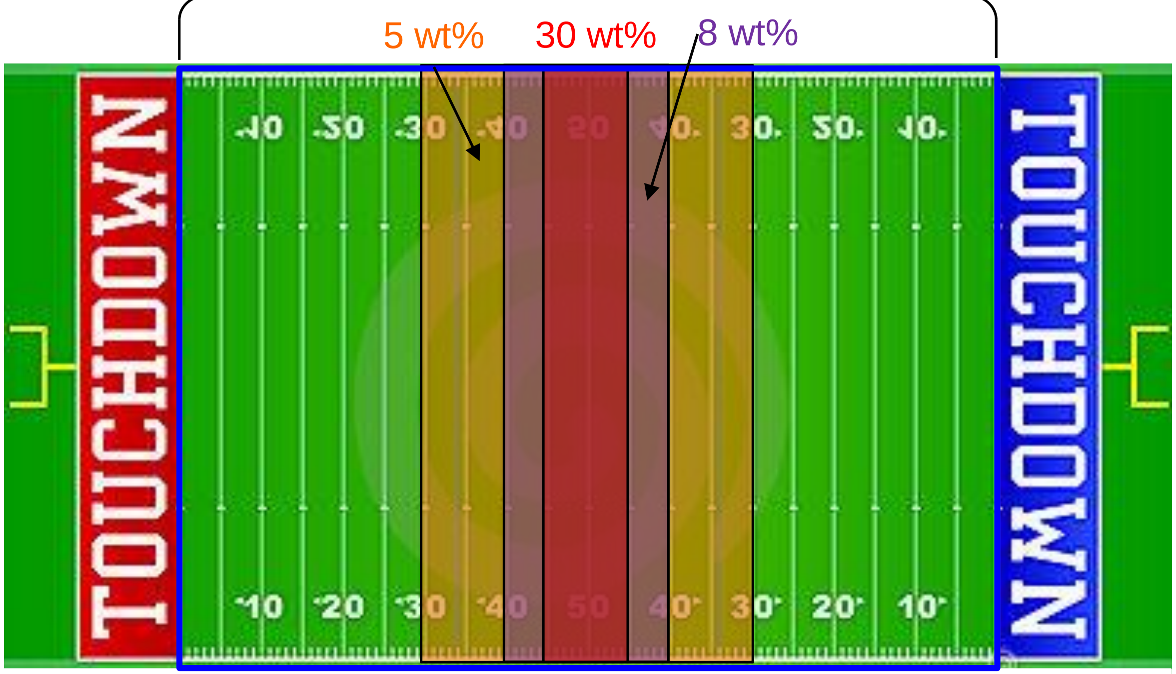
- Analog field test show oxygen extraction from regolith doesn't required excessive processing equipment/infrastructure





Human Mission Mars Soil Excavation for Water

3 wt% water; 7.7 cm deep



H_2O 1.238 kg/hr
480 days

Soil 1500 kg/m3
Ice 940 kg/m3

Water wt%	Soil wt%	Water kg	Soil kg	Total kg	Ave Density kg/m3	Tot Vol m3	FB Depth cm	FB Field yds
3	97	14261.76	461130.2	475392.0	1483.20	320.52	7.67	100.00
5	95	14261.76	270973.4	285235.2	1472.00	193.77	4.64	60.46
8	92	14261.76	164010.2	178272.0	1455.20	122.51	2.93	38.22
30	70	14261.76	33277.4	47539.2	1332.00	35.69	0.85	11.14
70	30	14261.76	6112.2	20373.9	1108.00	18.39	0.44	5.74

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov